Super-Parameterization of Boundary Layer Roll Vortices in Tropical Cyclone Models

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Award Number: N000141210447

LONG-TERM GOALS

The long term goals of this effort are to

- Advance the parameterization of the atmospheric boundary layer in high wind conditons to improve the forcasts of tropical cyclone (TC) intensity and
- Develop and implement a new parameterization of the effects of roll vortices into the U.S. Navy's oprational COAMPS-TC prediction system.

OBJECTIVES

The objectives of this project are:

- To develop a new methodology for explict representation of roll vortices in TC models.
- To investigate the mechanisms leading to the formation of roll vortices in TC conditions and to assess their effects on the structure and intensity of TCs.
- To inverstigate the interaction between the surface processes and the BL processes and to assess their effects on TC intensity and structure preditions.

APPROACH

Our approach to parameterization of roll vortices in a TC model resembles the "super-parameterization" approach used to simulate cloud physics processes in general circulation models. This methodology includes embedding a roll vortex resolving high-resolution 2-D LES model into the 3-D equation system representing a TC model. The decomposition of a 3-D equation system into two coupled equation systems for the mean flow and convective scale motions (roll vortices) is described in detail by Ginis et al. (2004) for an idealized 2-D mean flow. In this project, we extended this procedure for a general case of a 3-D TC model. The two models are coupled and explicitly solve the two-way interaction between the large-scale flow and roll vortices.

Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE **30 SEP 2013**	2. REPORT TYPE	3. DATES COVERED **00-00-2013 to 00-00-2013**
4. TITLE AND SUBTITLE **Super-Parameterization of Boundary Layer Roll Vortices in Tropical Cyclone Models**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Rhode Island,Graduate School of Oceanography,215 South Ferry Rd,Narragansett,RI,02882**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

WORK COMPLETED

Tasks completed:

- We studied the generation of roll vortices due to the inflection point instability (IPI) in an idealized TC boundary layer. The effects of wind and stratfication on the formation and characteristics of rolls were investigated. The results were summarized in a manuscript submitted to *J. Atmos. Sci* (Gao and Ginis, 2013).
- We inverstigated the two-way interactions between IPI-generated rolls and the mean HBL flow.
- We began analyzing the HBL wind and stratification profiles produced by idealized COAMPS-TC simulations to investigate the disctinct characteristics of dynamical and thermal instabilities and the associated roll generation mechanisms.

RESULTS

1. Interactions between IPI-generated rolls and the mean HBL flow

1.1 Effects of rolls embedded in HBL at different locations

To investigate the effect of rolls local mean wind profiles we embedded the 2D-LES model at preselected locations within the HBL. Here we show the experiments conducted at two locations: 40 km (1.0 RMW) and 80 km (2.0 RMW) from the storm center. The turbulent mixing coefficient K is parameterized with the following scheme: $K = l^2 \cdot S \cdot \sqrt{1-Ri}$, where *S* is the vertical wind shear, *Ri* is the gradient Richardson number and *l* is the mixing length, given by $\frac{1}{l} = \frac{1}{\kappa z} + \frac{1}{l_\infty}$. The value of l_∞ used in these experiments is 20 m.

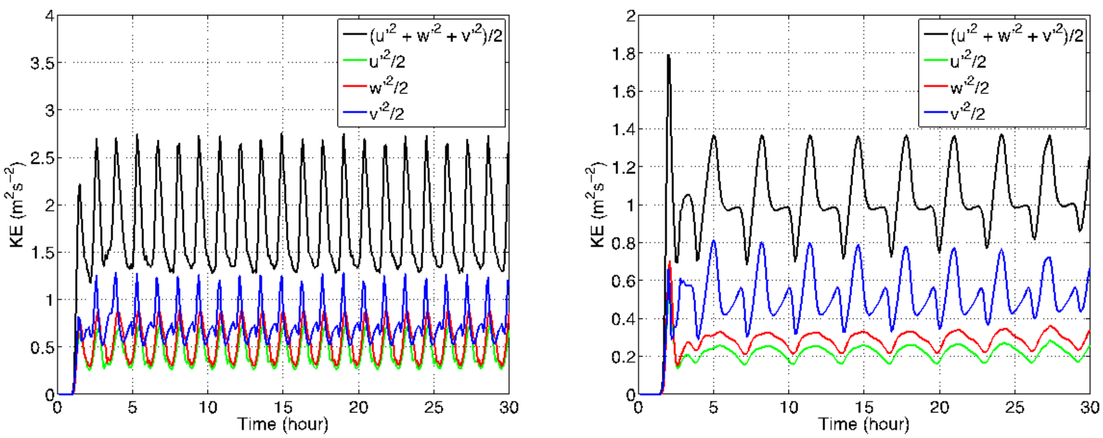

Figure 1. Time series of domain-averaged kinetic energy of rolls. Left: rolls at 1.0RMW; Right: rolls at 2.0 RMW.

a. Inertial oscillation triggered by rolls

As shown in Fig.1, rolls reach nonlinear phase after a brief period of exponential growth in both experiments. In the nonlinear phase, the kinetic energy (KE) of rolls oscillates with time. The period of the oscillation varies with radius. Fig.2 shows the time series of the cross-roll mean flow. After the rolls reach nonlinear phase, the roll-induced fluxes start to act on the mean flow. Similar to the KE of rolls, the mean flow also oscillates with time, with the same period as the KE. Due to the conservation of angular momentum, the hurricane flow has an intrinsic oscillation mode, which is comparable to the inertial oscillation in common geophysical problems. The angular frequency of such oscillation is given by: $I = \sqrt{(f + \frac{2\bar{V}_g}{r})(f + \frac{\bar{V}_g}{r} + \frac{\partial \bar{V}_g}{\partial r})}$, where $\bar{V}_g$ is the gradient wind.

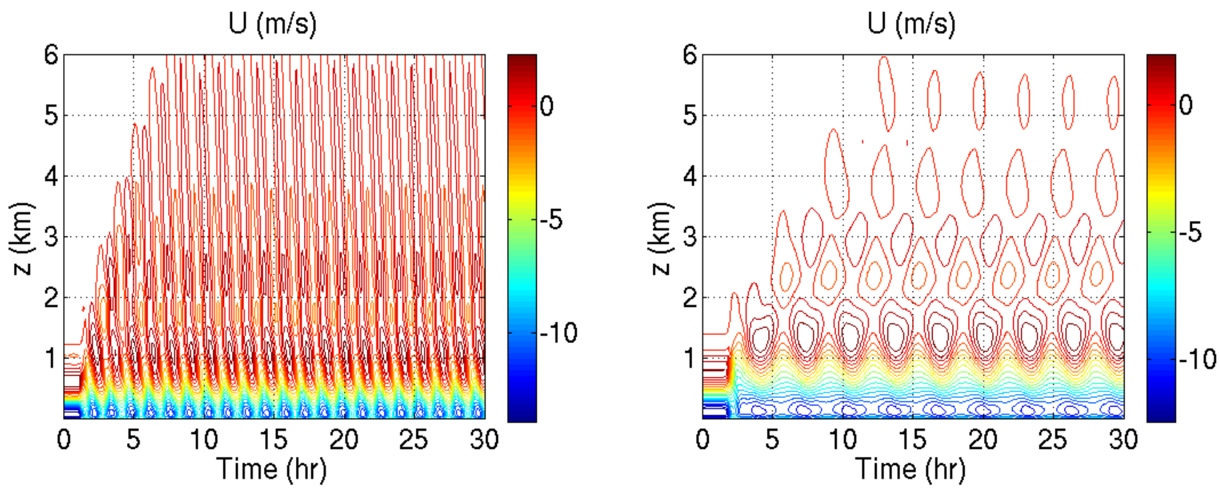

Figure 2. Time series of cross-roll mean flow. Left : crolls-roll mean flow at 1.0RMW; Right: cross-roll mean flow at 2.0 RMW.

The spectral analysis confirms that the oscillations in the mean flow are the inertial oscillations. Fig.3 shows spectra of the cross-roll mean flow at different heights in the two experiments. The oscillations have the same period at different heights. At 1.0 RMW, the period derived from spectral analysis is 1.37 hour, while the period estimated based on $2\pi / I$ is 1.26 hour. At 2.0 RMW, the period derived from spectral analysis is 3.35 hour, while the period estimated based on $2\pi / I$ is 3.65 hour. Therefore, we can conclude the oscillations in the mean flow are indeed inertial oscillations, which are triggered by the rolls when they reach nonlinear phase.

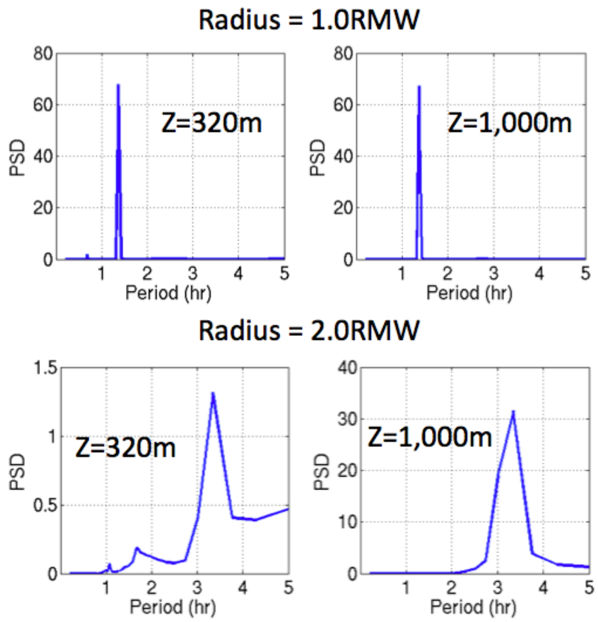

Figure 3. Spectra of the cross-roll mean flow at two different heights, 320 m and 1000 m, at 1.0 RMW (upper panels) and at 2.0 RMW (low panels).

b. The effect of rolls on the HBL mean flow

Besides the inertial oscillations, rolls also induce other effects on the mean flow. Fig.4 shows the total momentum fluxes before and after rolls are introduced at 40km (1.0 RMW) from the storm center and the wind profiles before and after the rolls are introduced. To filter out the inertial oscillation, we applied a 10-hr averaging. The rolls greatly enhance the total momentum fluxes in the boundary layer. As a result, the radial (inflow) wind speed is reduced and the inflow layer height is increased. In addition, the maximum tangential wind is reduced as well.

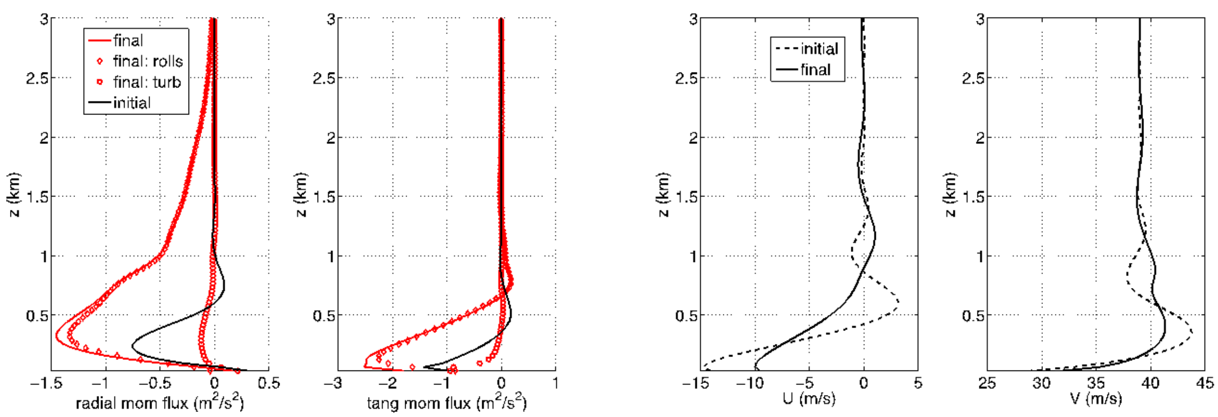

Figure 4. Momentum fluxes and mean flow profiles with and without the rolls effect at 1.0 RMW. At the left two panels, black lines represent the initial momentum fluxes, which are turbulent fluxes only. Red solid lines represent the total fluxes, which are the combination of roll-induced fluxes (red diamonds) and turbulent fluxes (red circles). At the right two panels, dashed lines represent the initial mean flow profiles (no rolls).

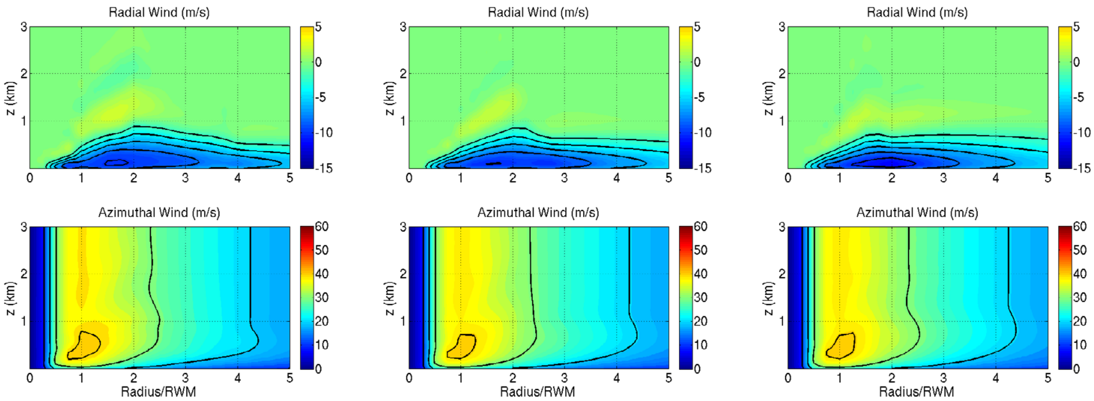

Figure 5. Averaged mean flow with the rolls effect. From left to right: l_∞= 20m, 30m and 40m. The contour interval is 2m/s for the radial wind and 10m/s for the azimuthal wind

1.2 Impact of rolls on the overall HBL wind structure

We further investigated the impact of roll vortices on the overall wind structure of the HBL by placing the 2D-LES at every grid points in the mean flow domain, ranging from 1.0 RMW to 4.0 RMW. In the presence of stratification, rolls are not always be generated. Only when l_∞ is sufficiently small, leading to a strong vertical wind shear, rolls can be generated. Five experiments were conducted with different vales of l_∞: 20m, 30m, 40m, 60m and 80m. Rolls were not generated in the last two experiments, i.e., when l_∞= 60m and 80m. Generally, the HBL wind structures with the rolls effect (Fig.5) are quite similar to the HBL wind structure without rolls effect, but with the use of relatively larger values of l_∞(Fig.6). Fig.7 shows the wind profiles at 1.0 RMW with and without the rolls effect for different values of l_∞. After the rolls are introduced, the wind profiles converge, even though the initial wind profiles are different. This suggests the effects of rolls on the mean wind could be represented by using a relatively large value of l_∞.

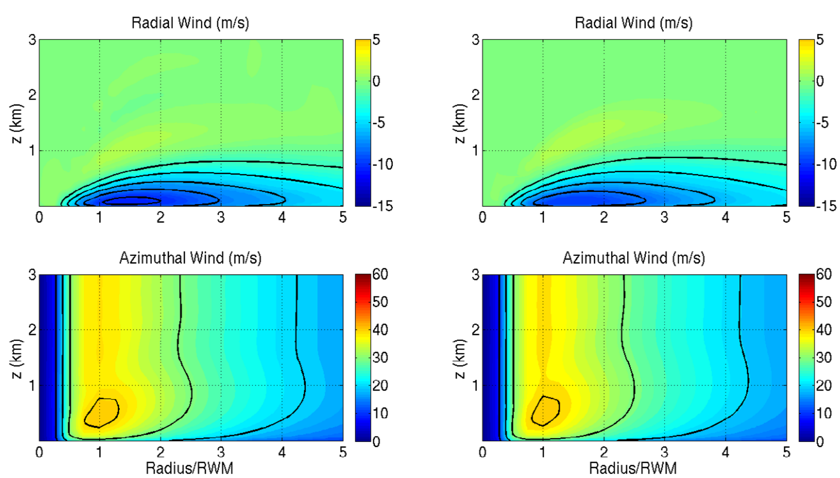

Figure 6. Steady-state mean flow without the rolls effect. From left to right: l_∞= 60m and 80m. Contour intervals are the same as Figure 5.

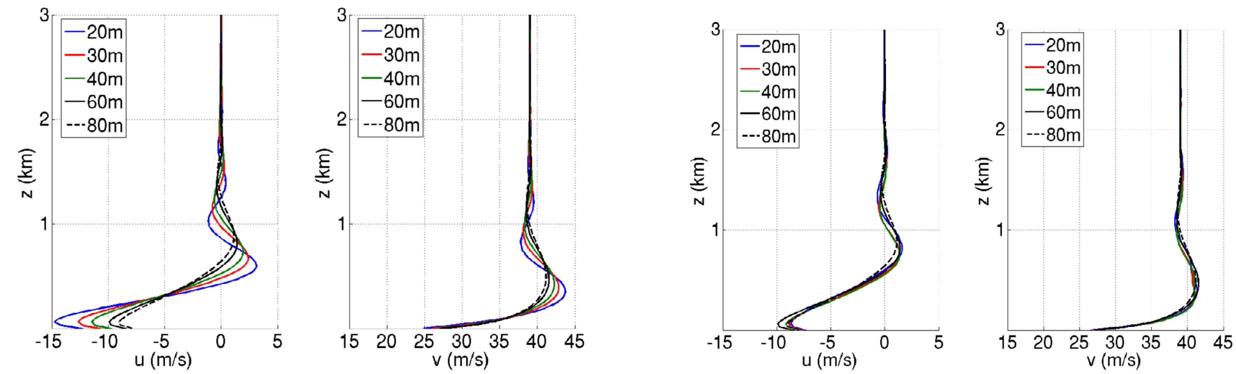

Figure 7. Steady-state mean flow without (two left panels) and with the rolls effect at 1.0RMW. The values of l_∞ are indicated in the legends.

2. Rolls simulations using COAMPS-TC model output

We conducted idealized experiments using the COAMPS-TC model. The wind and potential temperature profiles from these experiments were used to run the 2D LES model. We found two types of instability to be responsible for the generation of rolls in COAMPS-TC: inflection point instability and thermal instability. Rolls generated by these two types of instability have very distinct characteristics (Fig.8 and Fig.9). Rolls generated by the inflection point instability have a relatively larger wavelength and the streamlines are tilted near the surface. In contrast, rolls generated by the thermal instability have smaller size, and their streamlines are more symmetric. These two different generation mechanisms may help to explain the diverse wavelengths (~500m to ~6km) of rolls observed in hurricanes.

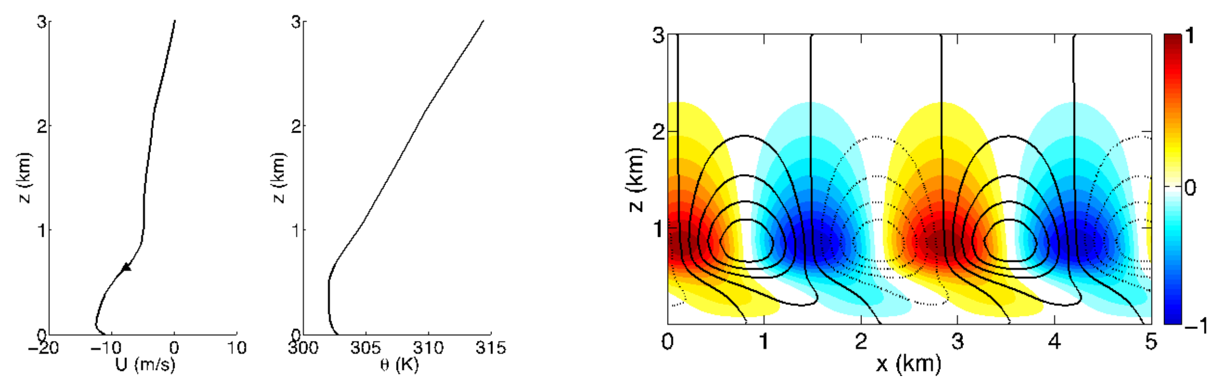

Figure 8. Left: wind and potential temperature profiles from the COAMPS-TC idealized experiment favorable for inflection point instability. The location of the inflection point is indicated by the black triangle. Right: rolls generated from these profiles by the 2D-LES model. Colors represent nondimensional vertical velocity, contours represent streamlines.

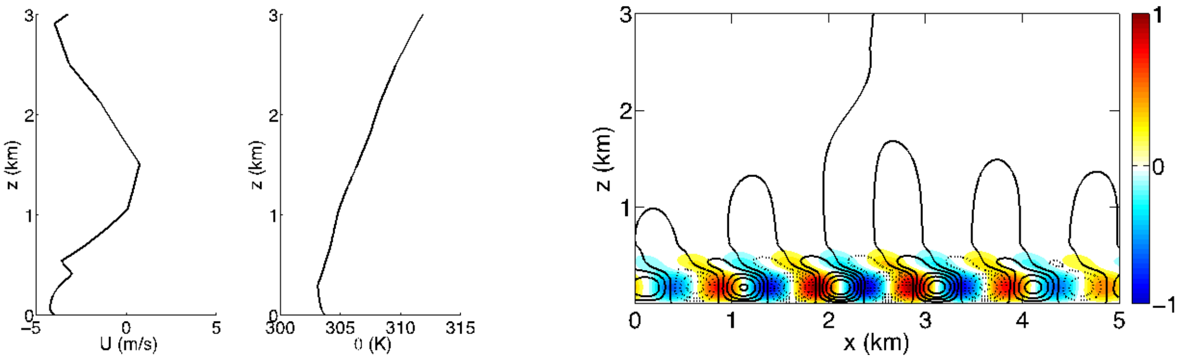

Figure 9. Left: wind and potential temperature profiles from the COAMPS-TC idealized experiment favorable for thermal instability. Right: rolls generated from these profiles by the 2D-LES model. Colors represent nondimensional vertical velocity, contours represent streamlines.

IMPACT/APPLICATIONS

This research program will advance the understanding and parameterization of the atmospheric boundary layer in tropical cyclone conditions as a route toward skillful prediction of tropical cyclone intensity and structure. A new parameterization of the effect of roll vortices will be developed and implemented into the U.S. Navy's operational COAMPS-TC prediction system.

RELATED PROJECTS

Other ONR DRI "Unified Parameterizaiton for extended Range Prediction" projects.

REFERENCES

Ginis, I., A.P. Khain, E. Morozovsky, 2004: Effects of large eddies on the structure of the marine boundary layer under strong wind conditions, *J. Atmos. Sci.,* **61**, 3049-3064.

Gao, K. and I. Ginis, 2013: On the generation of roll vortices due the inflection point instability of the hurricane boundary layer flow (submitted to *J. Atmos. Sci.*).